Quasi 3D Photonic Crystal Structures on SOI

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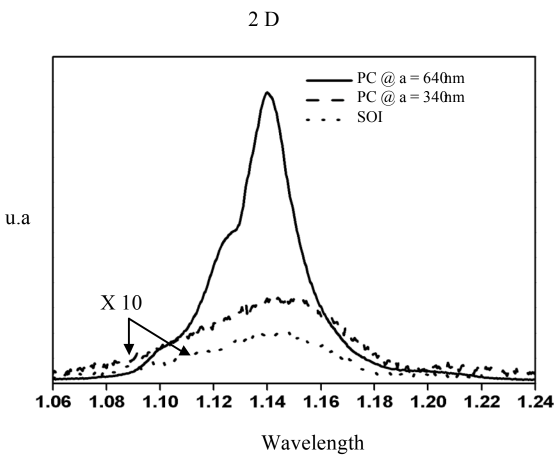
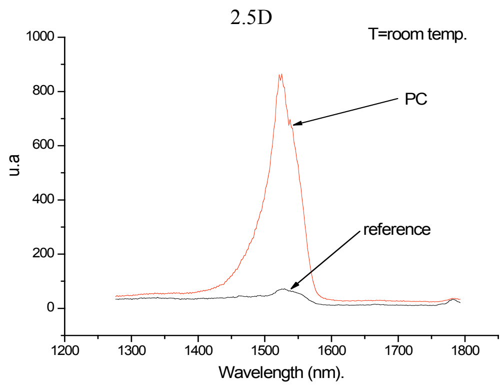
So far optical confinement in 3 dimensions has been demonstrated but still requires hard technological steps. We propose here a new way of realising optical confinement in the three space dimensions by assembling SOI based 2D and 1D photonic crystals (PC).From that quasi 3D samples were designed, build, and optically characterised.

We have first made one dimension silicon photonic crystals, called silicon on mirror (SOM),by bonding a SOI substrate and SiO_2/Si_3N_4 multilayers. These SOM, designed for 1.15µm or 1.54µm, where then associated with 2D PC. These 2D PC had been previously optically characterised and showed light extraction enhancement up to 70 times at low temperature for devices working at1.15µm and up to 20 at room temperature for those designed for 1.54µm.Then these 2D+1D boxes were experimentally investigated and showed light extraction enhancement up to 30 times at room temperature.





Finally we did calculation in such 2.5D photonic devices and point out the important role of the SiO_2 spacer layer between the 2D PC and the Bragg reflector. We show, that according to the thickness of this layer, the coupling of the 2D and the 1D PC can be tuned and thus the Q of the 2D PC or light extraction from the top can be greatly enhanced.

Spectral analysis in the visible range of light transmission through sub-wavelength annular apertures arrays in gold films

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Baida and Van Labeke recently proposed a structure which exhibits a supertransmission of light through metallic films pierced by submicronic apertures. This structure consists of an array of nanometric coaxial apertures in a metallic film and it has been named AAA: Annular Aperture Array [1,2,3].

Our first structure consists of a large array of coaxial apertures with inner and outer diameters of 250nm and 330nm respectively and a grating period of 600nm in 150nm gold film (for the fabrication procees see ref. [4]). It experimentally shows a transmission peak at 700nm around 17% and it fits very well to the theoretical spectral response obtained by FDTD calculation (to be published in *Optics Letters*).

We propose here new structures with an enhanced transmission: the different parameters (period, inner and outer diameter) had to be redesigned and optimized so that these structures exhibit a supertransmission of light of 80% such as in reference [1].

[1] F.I. Baida and D. Van Labeke, Optics Commun. 209, 17 (2002).
[2] F.I. Baida and D. Van Labeke, Phys. Rev. B 67, 155314(2003).
[3] D . Van Labeke, F.I. Baida and J.M. Vigoureux, J.Microscopy, 213, 140 (2003).
[4] A.Perentes, I. Utke, B. Dwir, M. Leutenegger, T. Lasser, P. Hoffmann, F. Baida, M.-P. Bernal, M. Russey, J. Salvi and D. V. Labeke, Nanotechnology (2004).

High efficiency defect-based photonic-crystal-tapers designed by a genetic algorithm

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A method based on a genetic algorithm (GA) is used to design the optimum configuration of defects that when put within a photonic crystal (PhC) taper improve the coupling efficiency between dielectric and PhC waveguides [1]. One of the most popular GAs used in combination with multiple scattering theory is considered [2]. This approach optimises the whole configuration of defects simultaneously and, therefore, takes into account the correlation among the defects. Transmission efficiencies up to 94% have been predicted for a 3μm-wide dielectric waveguide into a single-line defect PhC waveguide. This result significantly improves the transmission efficiency of the same PhC taper without defects. On the other hand, the influence of the PhC-taper length on the coupling efficiency has also been analyzed. It is obtained that resonant modes can be excited when the length of the PhC-taper is increased thus degrading the coupling efficiency. However, these resonant modes can be avoided by carefully designing the PhC taper geometry.

[1] P. Sanchis, *et al* "Experimental demonstration of high coupling efficiency between wide ridge waveguides and single-mode photonic crystal waveguides", IEEE Photon. Tech. Lett., vol. 16, pp. 2272-2274, 2004.

[2] A. Håkanson, José Sánchez-Dehesa, and L. Sanchis "Inversed design of photonic crystal devices", to be published IEEE J. Sel. Areas in Commun, 2005.

Semi-analytic approach for coupling issues in photonic crystal structures

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A semi-analytic approach based on previously derived closed-form expressions for the transmission and reflection matrices between a dielectric waveguide and a semi-infinite photonic crystal (PhC) waveguide [1,2] is proposed for analyzing coupling issues in PhC structures. The proposed approach is based on an eigenmode expansion technique and introduces several advantages with respect to other conventional numerical methods such as a shorter computation time and the possibility to calculate parameters, such as the reflection into PhC structures, difficult to obtain with others methods. Two different examples are analyzed and results compared to finite-difference time-domain (FDTD) simulations to prove the usefulness of the proposed approach: (i) an especially designed two-defect configuration placed within a PhC taper to improve the coupling efficiency and (ii) a coupled-cavity waveguide (CCW) coupled to a single-line defect PhC waveguide by using an adiabatic taper.

[1] P. Sanchis, P. Bienstman, B. Luyssaert, R. Baets, and J. Marti, "Analysis of butt-coupling in photonic crystals", IEEE Journal of Quantum Electronics, vol. 40, pp. 550, 2004.

[2] P. Sanchis, J. Martí, B. Luyssaert, P. Dumon, P. Bienstman and R. Baets, "Analysis and design of efficient coupling in photonic crystal circuits", to be published in Optical and Quantum Electronics.

Effects of the lattice orientation and the interface termination on negative refraction in 2D photonic crystals

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Negative refraction at the interface between air and a 2D square photonic crystal (PhC) at frequencies corresponding to the second band is analysed by means of equifrequency contour (EFC) diagrams and FDTD simulations. Several lattice orientations inside the slab giving rise to different slab terminations are considered to observe the influence of the lattice and the termination over the EM propagation. In principle, from the EFC analysis it could be established that if the EFC has a rounded shape and its radius decreases with frequency, the PhC should behave as a refractive medium with a negative effective index. However, we find that these conditions are not sufficient for the PhC to behave as a negative refractive medium. EM propagation inside the PhC is highly sensitive to the lattice orientation and the interface periodicity. It can be stated that a negative refractionlike behavior can only be observed when the interface is periodic and the mode symmetries of the external plane wave and the Bloch wave inside the PhC are matched. Even under this assumption, the Snell's law is not satisfied if the interface is not properly selected because the EFC retains a slight square-like shape even for frequencies near the bandgap. In addition, when the Snell's law is met the Goos-Hänchen effect for a finite slab has to be considered to obtain the effective index of refraction.

Mimicking amphoteric refraction in photonic crystals

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Recently, it was reported that at the interface between an isotropic medium and a uniaxial crystal (or between two uniaxial crystals) a phenomenon known as amphoteric refraction, this is, positive as well as negative refraction, can take place. We show that from an analysis of the equifrequency surfaces and properly choosing the interface, a two dimensional photonic crystal can also present amphoteric refraction, as depicted in Fig. 1. However, total transmission is difficult to achieve because a Bloch mode is excited inside the photonic crystal and the coupling efficiency from this mode to an external plane wave is less than unity.

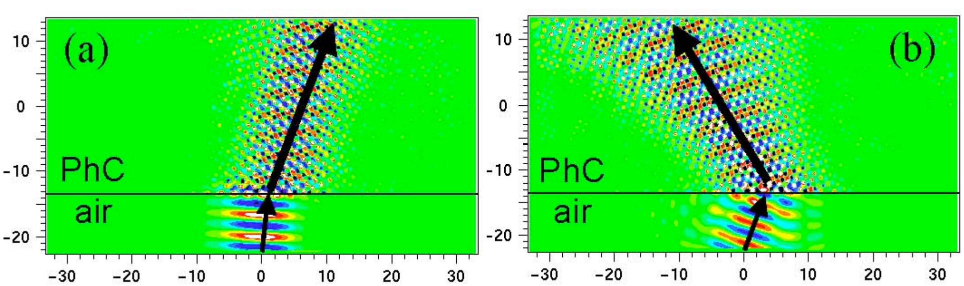

Figure 1: amphoteric refraction at the air-PhC Interface: (a) positive, (b) negative refraction.

Gigantic Enhancement of Magneto-Chiral Effect in Photonic Crystals

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We theoretically propose a method to enhance dramatically a magneto-chiral(MC) effect in photonic crystals. The MC effect is a directional birefringence even for the unpolarized light. This effect occurs in a material such as GaFeO3[1] in which both time-reversal and inversion symmetries are simultaneously broken. Unfortunately the wavevector dependence of a dielectric function due to the MC effect is typically the order of 10^{-6}, which is too small to be observed experimentally. We investigate the MC effect in two kinds of one-dimensional structures; (i) multilayers and (ii) stripes composed of the magneto-chiral medium and air. In both cases, the difference in the reflectivity with respect to different magnetization configurations is thousands of times enhanced compared with that in a bulk material.

[1] M. Kubota *et al.*, Phys. Rev. B **92**, 137401 (2004).

3D macroporous silicon photonic crystals with large complete photonic bandgap

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Recently a new 3D photonic crystal structure consisting of two triangular pore sets, which intersect each other orthogonally, was proposed. The structure has orthorhombic symmetry and its Brillouin zone resembles a slightly stretched fcc-zone. For optimized structure parameters and silicon as a matrix material a complete photonic bandgap of 25% is predicted.

We demonstrate the experimental realization of this structure applying a two- step process. A photoelectrochemical etch process creates the first triangular set of macropores with high aspect ratios in silicon. Subsequently a focused ion beam is used to drill the second pore set from the side. The lattice constant of the triangular pore sets is 500nm and the pore diameter around 380nm. Reflection measurements along different crystallographic directions reveal the spectral position of the bandgap in the near infrared around a wavelength of 1.3 micrometers [1]. The influence of experimental errors (e.g. shift, tilt and rotation of the two pore sets) on the size of the bandgap are studied by bandstructure calculations. From this the fabrication tolerances are concluded to assure structures with bandgaps above 10%.

[1] J.Schilling, A. Scherer, G. Stupian, R. Hillebrand, U. Gösele, *Applied Physics Letters* **86**, 011101 (2005).

Negative Index Aberrations

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Negative refraction has been demonstrated computationally and experimentally in photonic crystals[1,2]. There has even been some success in obtaining super resolution from negative refracting PC slabs, i.e. "perfect lenses"[2]. While a "perfect lens" would offer unique capabilities for near field focusing, the vast majority of optical devices must operate on far field radiation, which is unaffected by homogenous slabs. We have examined the application of negative index media to traditional, curved, far field lenses. We find that these negative index lenses offer clear performance advantages over their positive index lenses counterparts.

We examine the Seidel aberrations of thin spherical lenses composed of media with refractive index not restricted to be positive. We find that consideration of this expanded parameter space allows for the reduction or elimination of more aberrations than is possible with only positive index media. In particular, we find that spherical lenses possessing real aplanatic focal points are possible only with a negative index. We perform ray tracing that confirms the results of the aberration calculations[3].

[1] S. Foteinopoulou, E. N. Economou, and C. M. Soukoulis, *Phys. Rev. Lett.* **90**, 107402 (2003).
[2] E. Cubukcu, K. Aydin, E. Ozbay , S. Foteinopolou, C. M. Soukoulis, *Phys. Rev. Lett.* **91**, 207401 (2003).
[3] D. Schurig, D.R.Smith, *Phys. Rev. E,* **70**, 065601 (2004).

Entangled-Guided Photon Generation in 1+1 D photonic crystals

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It is well known that photonic crystals (PhC) can support confined electromagnetic propagation. We consider a 1-D photonic crystal as a multi-channel waveguide for generating counterpropagating twin photons by spontaneous paramentric down-convertion. Considering $k_{\omega p}$ the wave-vector of the pump field at frequency ω_p tuned at the band-edge of the transmission spectrum for a normal incidence, $\beta_{\omega(s,p)}$ and $\beta_{\omega(i,s)}$ the wave-vector z-component of the generated-guided modes at the signal frequency (ω_s) and idler frequency (ω_i) respectively p and s polarized, if the non linear layer thickness is small enough there is no mis-match in x direction so the momentum conservation needs to be fulfilled only along the z direction. Due to the modal dispersion of the structure, the momentum conservation can be fulfilled for different frequencies with different polarizations that is $\beta_{\omega(s,p)} = \beta_{\omega(i,s)}$. Because of the symmetry of our structure we can write the photon pair emitted along the z-axis as a entangled state, more precisely: $|\psi\rangle = \frac{1}{\sqrt{2}}\left(|p,up;s,down\rangle + |p,down;s,up\rangle\right)$. Note that the counterpropagating down-converted twin photons are entangled in frequency, momentum and polarization.

Engineering waveguides in holographically-defined photonic crystals

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Waveguides and resonators that exploit the high level of optical isolation achieved within a photonic crystal have the potential to increase the packing density of integrated optical components by 10^4~10^6. We demonstrate the use of two-photon microfabrication to create optical device structures within a 3D holographically-defined photonic crystal.

Holographic lithography uses a 3D interference pattern to define the microstructure of a photonic crystal. The periodic light intensity generates a periodic distribution of H^+ ions by single-photon excitation of a photoacid generator (PAG). Using a confocal microscope we can map and modify the photoacid distribution; acid-catalyzed polymerization is then initiated by heating. An acid-sensitive dye is used to generate a 3D photoacid map; additional structure is generated by two-photon excitation of the PAG at the microscope's focus. During development, material that has received below-threshold exposure is removed to reveal the photonic crystal incorporating precisely positioned structural defects - the building blocks of photonic crystal waveguides. Waveguides buried within the depth of the developed crystal are imaged by confocal microscopy by using a second dye to infiltrate the voids in the structure.

Bound states in two dimensional graded photonic crystal at Γ point
A new approach to inhibit spontaneous emission

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When the photonic band in the light cone (A in the figure) was excited, the photon will propagate in the crystal but this photon can tunnel to the photon in air. The direction of this photon in air is given by $\cos\theta = k_B / k_L$ where k_B is the momentum of photon in the band, k_L is the momentum in air and θ is the angle from perpendicular direction. At Γ point (B) photon will move in the crystal with a very slow group velocity and also escape to the perpendicular direction. Then if bound state in the gap was fabricated (C), this photon cannot move in the crystal and all the light should go out from the crystal to the perpendicular direction.

The field intensity was calculated by the multiple scattering theory in the graded photonic crystal in which lattice constant changes gradually. We confirmed the existence of bound states at Γ point.

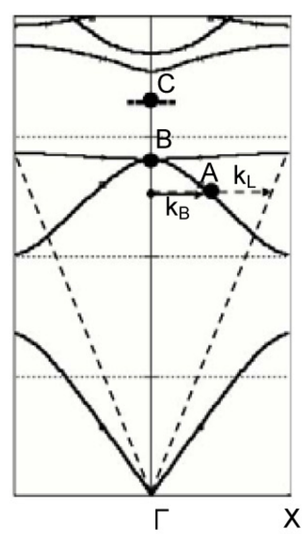

Fig.1. Typical band structure of the square lattice photonic crystal. Solid lines are the light lines.

Y-splitters in photonic wires and photonic crystal waveguides

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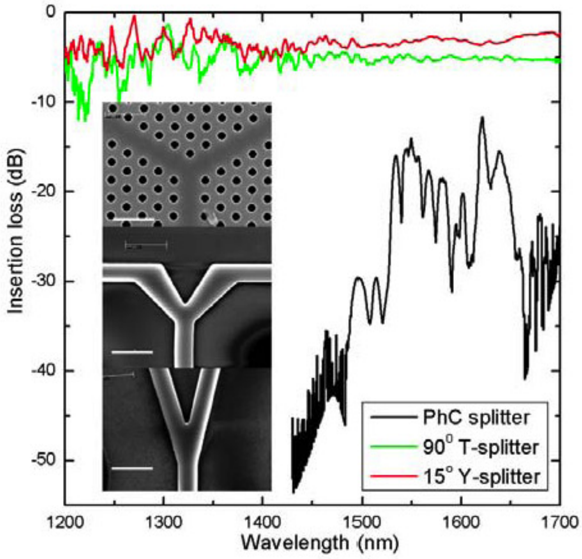
Development of wide-angle Y-splitters with micron-scale footprint areas is crucial for implementing dense optical integrated circuits. We compare the transmission bandwidth, return losses and total losses of 60° splitters based on W1 photonic crystal (PhC) waveguide with those of resonant 90° T-type and quasi-adiabatic 15° Y-splitters based on photonic wires. We find that for a non-optimized 60° PhC splitter the losses are around 6-7dB/split. Its low-loss spectral bands are separated by narrow bands with over 30dB higher attenuation. These high-loss bands correspond to the building up of strongly resonant modes (Q~800) due to intense back-reflections. Although it is possible to decrease the splitting losses by optimizing the structure's topology, the existence of these lossy resonant modes is intrinsic to highly resonant structures such as PhC waveguides. To solve this problem we study Y-splitters based on photonic wires with a footprint even smaller than that of a PhC-based device. The use of a low-Q resonant structure forming a 90° T-splitter minimizes the back-reflections and results in a nearly flat transmission spectrum over 200nm in bandwidth and with losses of only 2.6±0.7dB/split. Surprisingly, the quasi-adiabatic non-resonant Y-splitter provides even better performance with the total losses below 0.7dB/split.



Slow light photonic crystal waveguides

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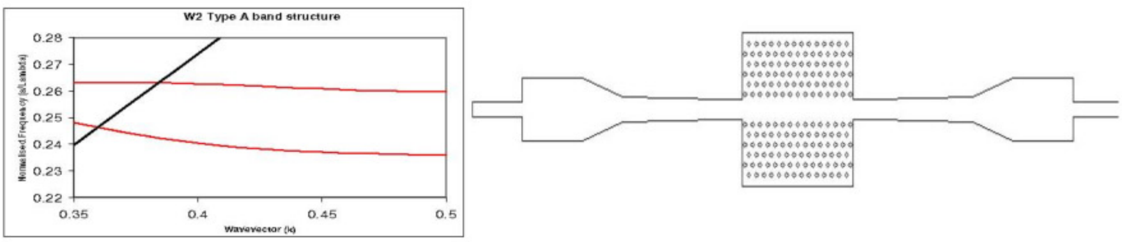
Slow light offers many opportunities for photonic devices by increasing the effective interaction length of imposed refractive index changes. The slow wave effect in photonic crystals is based on their unique dispersive properties and thus entirely dielectric in nature.

In Silicon-On-Insulator material, low loss operation requires that one should operate below the silica light line and thus restricts the useable region of the band structure. By injecting into higher order modes we can use a flat non-dispersive band whilst staying below the light line. The injection in to the higher-order modes can be achieved using a multi-mode interference device as shown below.



Left: Calculated band structures for W2 waveguides. Right: Schematic of projected device including injector into slow mode.

Out-Of-Plane Scattering Loss Reduction With Annular Holes

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Out-of-plane scattering within etched holes leads to photonic crystal device losses. We propose using annular holes to reduce diffraction losses (fig 1). Fig 2 compares losses of our scheme and standard holes calculated numerically. The bandstructure is not

highly influenced by the introduction of the inner pillar.

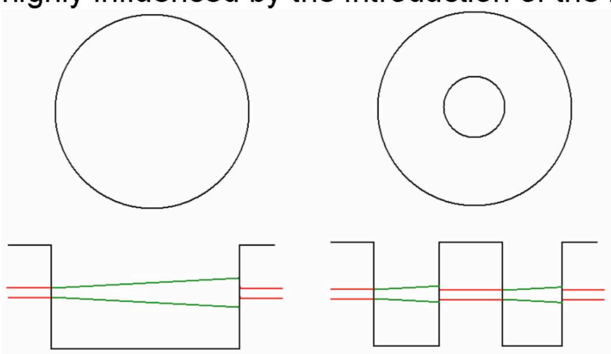

Fig 1. Schematic of losses from standard hole (left) and annular hole (right).

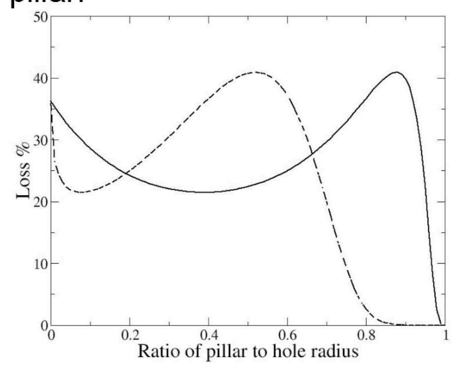

Fig 2. Loss of annular hole (solid) and hole with same filling factor (dashed).

Discreteness effects in left-handed metamaterials

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We present the study of a novel physics of composite left-handed metamaterials induced by interaction between the split-ring resonators (SRRs). We consider an example of the cubic lattice of parallel SRRs and study its linear and nonlinear properties. We demonstrate that the effective coupling between the resonators is highly anisotropic, and we derive the discrete coupled-mode equations for describing the propagation of magnetization waves. We show the existence of linear waves of magnetization, and also demonstrate that, in the nonlinear regime, magnetic response of a nonlinear metamaterial may become bistable, and we analyze modulational instability of different nonlinear states. We predict that nonlinear metamaterials may support the propagation of domain walls (kinks) connecting the regions of different states of magnetization, and study their dynamics. Two out-of-phase kinks may create a magnetization domain; a possibility to control the dynamics of such domains is promising for a design of the structures with controllable magnetization and photonic crystals which parameters can be made tunable.

[1] I.V. Shadrivov, A.A. Zharov, N.A. Zharova, and Yu.S. Kivshar, arxiv:cond-at/0501653

Spontaneous parametric down conversion in 1 D photonic crystals

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We report calculations on spontaneous parametric down-conversion in multilayer structures showing the possibility of tailoring the photon-pair spectrum for quantum information applications. Despite of what happens for homogeneous media, phase matching conditions are not crucial and the role played by phase matching conditions is weaker than the contribution due to field’s overlap for finite size photonic crystals. This behaviour makes it possible to select a given non linear process to be extremely efficient while suppressing all the others. We simulated the spontaneous process by adding a white noise to the equation for the signal field and observing the generation of the idler. We performed a scan over the allowed frequencies and in a regime of very low conversion efficiency the results represent the spectrum of down converted photon pairs. We show that twin photon generation can occur in both forward and backward direction with narrow bandwidth and high brightness per mode if the device is properly designed. We also developed a quantum model in agreement with the semiclassical approach.

Canalization of sub-wavelength images by electromagnetic crystal

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The original regime of operation for some flat superlenses formed by a layer of an electromagnetic crystal is proposed and studied theoretically. Both analytical modelling and FDTD simulations are applied. The mechanism does not involve negative refraction and amplification of evenescent waves as it was suggested in many previous works devoted to slabs of left-handed media. The high-frequency (sub-wavelength) spatial spectrum of a source is canalized together with the plane-wave spectrum by the eigenmodes of the crystal. All eigenmodes have equivalent longitudinal (i.e. directed across the slab) components of the wave vector and equivalent group velocities (which are also practically longitudinal). When the normalized frequency is moderate (the wavelength is large with respect to the crystal period) this regime can be obtained with the use of semiconductor crystals. For the TE-polarization this can be a lattice of air holes in a semiconductor matrix. For the TM-case this can be a lattice of semiconductor rods. The regime can be implemented at the low normalized frequencies with the help of impedance cylinders (at microwaves these cylinders form capacitively loaded wire media) or even with simple metal cylinders. The resolution of the order wavelength/6 is demonstrated. The thickness of the superlens is not related with the distance to the source and the lens can be made thick enough to be mechanically stable. Possible applications in the near-field optical microscopy are discussed.

NONLINEAR RESPONSE OF SEMICONDUCTOR BRAGG REFLECTORS

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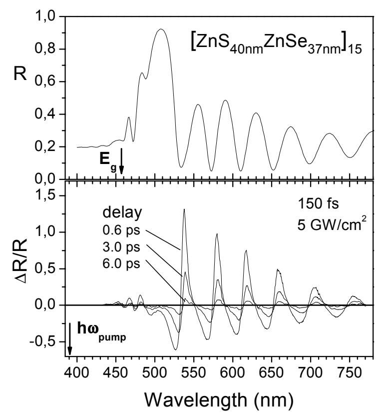

A nonlinear periodic structure is proposed and developed with the purposeful use of strong resonant intrinsic interband absorption in a semiconductor material, which causes modification of the material refraction index in the spectral range corresponding to morphological resonances formed by the periodicity of the structure. In the experiments, periodic ZnSe/ZnS heterostructures have been used and interband excitation of a ZnSe sublattice has been performed by nano-, pico- and femtosecond laser pulses. A considerable shift of reflection spectrum and large relative reflection changes were observed in a wide spectral range corresponding to the transparency region of ZnSe far from the intrinsic absorption onset. Evaluated refraction index change is about –0.05, the relaxation time being as short as 3 picoseconds. Relative reflection coefficient change exceeds 100%. In case of femtosecond excitation, a wide-band nonlinear response is observed for both one-photon near UV- and two-photon near IR-pulses. The nonlinearity relaxation time is supposed to depend a transition from non-equilibrium to quasi-equilibrium distribution of electrons and holes within ZnSe conduction and valence band, respectively, rather than electron-hole recombination time.

Fabrication of omnidirectional photonic band gap structures for photonic devices in the near infrared and visible frequencies

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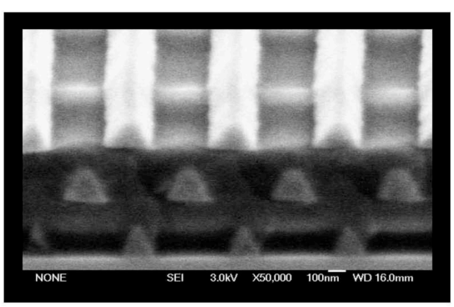
We describe the fabrication of a three dimensionally periodic crystal structure with omnidirectional band gap for devices in the near-IR and visible wavelength region using a technique of direct electron beam write coupled with multi-level alignment. This technique will allow us to fabricate prototype photonic band gap device structures with different materials in a direct way to test the effects of omnidirectional photonic gap on various optical phenomena (e.g. spontaneous emission, localization etc.). To demonstrate the feasiblility of this method we have successfully fabricated Iowa State“woodpile” structures with lattice spacings in the ~ 0.5 mm range. Prototype structures in the near –IR fabricated with silicon give a wide stop band in the stacking direction centered around 1.5 mm wavelength (figure 1) consistent with previously published structures. Woodpile structures fabricated with gold reveal a sharp band edge near ~1.0 mm wavelength with a broad high reflectivity region (close to 100%) for larger wavelengths. In this presentation we will describe the fabrication processes used and present optical characterization data from various structures.

The research at Sandia National Laboratories is supported by U.S. Departmentof Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.



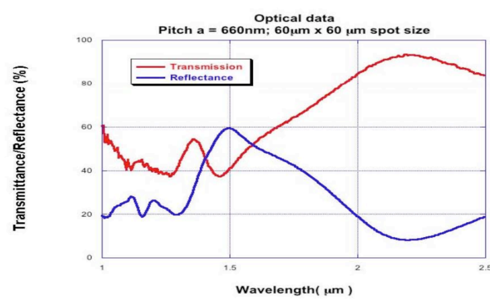


Figure 1.

Experimental demonstration of high-precision optical interference in Mach-Zehnder-type photonic crystal waveguide

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Excellent optical interference was experimentally demonstrated in the near infrared region using asymmetric Mach-Zehnder (MZ) type GaAs-based two-dimensional photonic crystal (2DPC) slab waveguides with directional couplers (DCs)[1], as shown in Fig. 1. As one of two MZ arm lengths changed in units of the lattice constant, the output intensities exhibited sinusoidal curves in excellent agreement with coupled-mode theory. In another experiment where the DCs were operated by two incident optical beams with externally controlled phase's difference, a sinusoidal change was observed also in output intensities according to the theory of the DC. These results were obtained by virtue of excellent nano-fabrication of the 2DPC structures and pave the way to successful operation of a PC-based ultra-small symmetrical MZ (SMZ) all-optical switch.

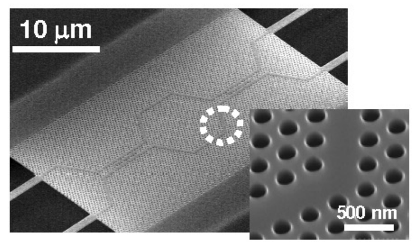

Fig. 1: SEM image of MZI.

[1] Y. Sugimoto et al. *Appl. Phys. Lett.* **83**, 3236 (2003).

Complete Three-Dimensional Bandgap in One-Dimensional Negative-Index Periodic Structures

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Negative-index (or left-handed) metamaterials with simultaneously negative real parts of dielectric permittivity and magnetic permeability can be used for novel applications, including enhanced sub-wavelength imaging. We reveal, for the first time to our knowledge, that a one-dimensional periodic structure with layers of negative-index material can possess, under certain conditions, *a complete three-dimensional bandgap* for both TE- and TM-polarized waves. In this case, the Green function characterizing radiation of a point source becomes exponentially localized because the electromagnetic waves cannot propagate through the structure at any angle. The existence of *one-dimensional structures made of transparent materials and possessing a complete three-dimensional spectral band gap* is a highly nontrivial and unexpected finding, which was not reported earlier. Our results are in a sharp contrast with all known properties of one-dimensional dielectric periodic structures, which can only possess partial spectral gaps that provide omni-directional reflection for a limited range of the incident angles. Indeed, light can always propagate through a dielectric structure due to coupling between guided modes supported by individual dielectric slabs, however we find that this tunneling mechanism can be suppressed in left-handed structures for certain values of dielectric permittivity and magnetic permeability when negative-index slabs do not support any guided modes, giving rise to complete two- and even three-dimensional bandgaps.

Tunable negative refraction in photonic lattices

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Propagation of light in photonic structures with a periodic modulation of the refractive index is defined through the diffraction properties of the extended eigenmodes in the form of Floquet-Bloch waves. At the boundaries of the structure, beams experience refraction at the angle proportional to the difference of the diffraction coefficients inside the structure and in a free space. Because the Bloch-wave diffraction depends strongly on the refractive-index contrast, this refraction could be effectively controlled if the lattice depth is dynamically modified. The differences in the diffraction properties of the Bloch waves corresponding to different bands of the transmission spectrum can be used to spatially separate them in the structure [1].

In this work we investigate both positive and negative refraction of light associated with different spectral bands of a photonic lattice. We predict theoretically and demonstrate experimentally *tunable negative refraction* of beams associated with the top of the second band of an optically-induced photonic lattice. We show tunability of the output beam position on the dynamically reconfigurable lattice depth. At higher laser intensities, the light becomes self-trapped propagating in the form of a spatial gap soliton [2], while preserving the basic steering properties and negative refraction.

[1] P. St. J. Russell, T. A. Birks, and F. D. Lloyd Lucas, "Photonic Bloch waves and photonic band gaps," in *Confined Electrons and Photons*, Eds E. Burstein and C.Weisbuch (1995), p. 585.

[2] D. Neshev, A. A. Sukhorukov, B. Hanna, W. Krolikowski, and Yu. S. Kivshar, Phys. Rev. Lett. **93**, 083905 (2004).

New Fabrication Method of Woodpile 3D Photonic Crystals

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Thus far, we have developed 3D photonic crystals (PCs) by wafer-fusion of striped layers [1], and investigated the light propagation and light emission phenomena [2]. In this symposium, we propose a new fabrication method of 3D PCs, which can be combined with the wafer-fusion technique. A drilling method is employed in stead of stacking of individual stripes. Fig.1 illustrates the method, where double etching process in the orthogonal directions [110] and $[1\bar{1}0]$ is performed to form woodpile structure.

The method can be combined with the wafer-fusion technique, and various defects and light emitters can be easily introduced. The details will be reported at the symposium.

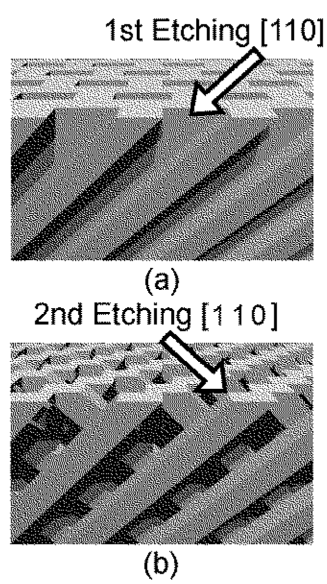

Fig.1. Double etching process in two orthogonal directions: (a) [110], (b) $[1\bar{1}0]$.

[1] S. Noda, K. Tomoda, N. Yamamoto, and A. Chutinan, *Science*, **289**, 604 (2000).

[2] S. Ogawa, M. Imada, S. Yoshimoto, M. Okano, and S. Noda, *Science*, **305**, 227 (2004).

Application of 3D Optical Wannier function method to Micro-circuitry 2D-3D Photonic Band Gap Heterostructures

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The finite-difference time domain (FDTD) method has been the workhorse for simulating optical propagation in photonic crystals. Typically this involves discretizing the 3D unit cell of a PBG material with more than 1000 points on which the vector field amplitude is defined. For complex 3D circuit paths, this becomes computationally cumbersome. The same information can be efficiently recaptured by representing the optical field in a 3D system as an expansion in small number of Wannier functions, the optical analogue of atomic orbitals in electrons [1-3].

We introduce the application of 3D optical Wannier function method to photonic crystals. We research Wannier functions in 2D-3D photonic band gap heterostructures [4] composed of 3D woodpiles, square spirals, and slanted pore architectures with 2D defect layers. By expanding electromagnetic fields by maximally localized Wannier functions, it becomes possible to calculate guided modes and transmittances in 3D circuit paths with optical devices in 3D PBG materials.

[1] N. Marzari, and D. Vanderbilt, *Physical Review B*, **56**, 12 847 (1997).
[2] I. Souza, N. Marzari, and D. Vanderbilt, *Physical Review B*, **65**, 035109 (2001).
[3] K. Busch, S. F. Mingaleev, A. Garcia-Martian, M. Schillinger and D. Hermann, *Journal of Physics Condensed Matter*, **15**, R1233 (2003).
[4] A. Chutinan, S. John, and O. Toader, *Physical Review Letters*, **90**, 123901 (2003), A. Chutinan and S. John, *Physical Review E* (2005) in press.

Selective Growth Technique for Hexagonal and Triangular Air-hole Arrays and Its Application to Air-bridge Type Photonic Crystal Slabs

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Selective area metal-organic vapor phase epitaxy (SA-MOVPE) on GaAs (111)B patterned substrates enables us to form sub-micron scale periodic nanostructures having atomically flat vertical sidewalls [1, 2]. Here, we report on the fabrication of air-hole arrays by SA-MOVPE and its application to photonic crystal slabs.

The samples are grown on patterned substrates having periodic SiO_2 hexagonal masks in 400-500 nm-pitch. In SA-MOVPE, growth occurs only in the regions without masks. As a result, hexagonal air-hole arrays are formed. By changing the growth conditions, it is possible to fabricate triangular air-hole arrays, because of lateral growth over the masks, which takes place only at three corners of hexagon. Furthermore, by employing selective under-cut etching, air-bridge type structure is fabricated as shown in Fig. 1.

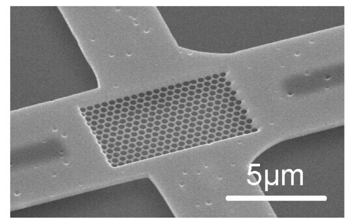

Fig. 1: SEM image of an air-bridge type structure

[1] S. Ando, N. Kobayashi and H. Ando, *Jpn J. Appl. Phys.* **32** (1993) L1293.
[2] T. Hamano, H. Hirayama and Y. Aoyagi, *Jpn J. Appl. Phys.* **36** (1997) L286.

Spectrally and spatially resolved lasing emission of an optically pumped Photonic Crystal : evidence of a 2D lasing mechanism

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M.Mulot and S.Anand
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Lasing in a full Photonic Crystal (PhC) is achievable through several feedback mechanisms according to the photonic gap involved. Some are akin 1D Distributed FeedBack "classically" implemented in DFB lasers, operating on a single direction of the PhC, and one is specific to the 2D PhC as it relies on a feedback mechanism which involves both directions, as clearly explained in [1].

We have measured lasing operation on a 2D PhC fabricated on a two wells+ cladding structure etched by CAIBE [2] . The lasing spectrum exhibits 2 lines which are not related to the finite size of the PhC, but could be attributed to the modal degeneracy close to the K point of the upper band. We also measured the spatial distribution of the emitted power. These measurements are discussed with respect to calculated dispersion curves and mode field distributions.

[1] M. Notomi, H.Suzuli and T.Tamamura , **Appl. Phys. Lett., 78**, 1325 (2001)
[2] M.Mulot, S.Anand, M.Swillo, M.Qiu, B.Jaskorzynska and A.Talneau, **Jour. Vac. Sci and Technol., B, 21**(2), 900 (2003)

1.55 μm Pure Photonic Crystal Waveguiding in Two Dimensions

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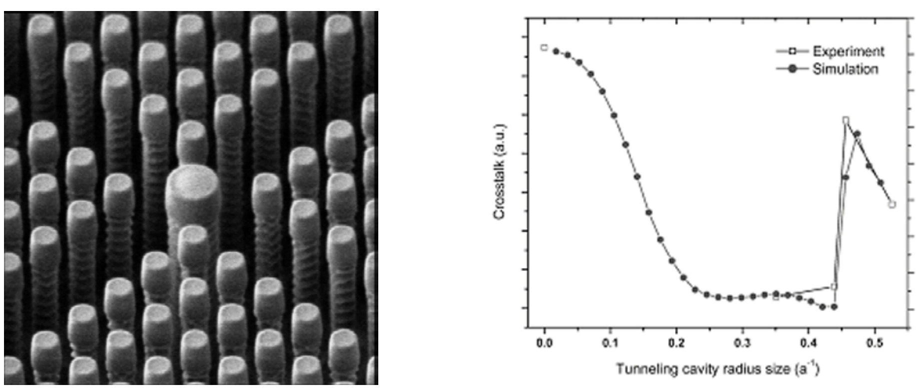
We report experiments of optical guiding in air at 1.55 μm wavelength in two-dimensional (2D) photonic crystal (PhC) waveguides. The deeply etched photonic crystal structure with crossing geometry and C_{4v}-symmetry tunneling cavities[1] of Fig. 1a was realized by deep reactive Ion etching for record sidewall scallop depth and aspect-ratio[1]. The radiation was guided only by effect of the 2D PhC, in the absence of other waveguiding mechanisms such as index guiding or reflecting planes etc. First principle simulation results were verified by experiment of both reflection and transmission measurements. The results obtained corresponded well with theoretical simulation results by finite-difference-time-domain method (see Fig. 1b), which indicate a critical value for the depth of etching required. At the same time, discrepancy between symmetry restricted and non-restricted orthogonal waveguide modes transmission measurements also revealed relation of cavity property to extend of radiation loss for such 2D PhC waveguides.

[1] Steven G. Johnson, Christina Manolatou, Shanhui Fan, Pierre R. Villeneuve, J. D. Joannopoulos, and H. A. Haus, *Opt. Lett*. **23**, 1855 (1998).
[2] Selin H. G. Teo, A. Q. Liu, J. Singh, M. B. Yu, *J. Vac. Sci. Technol. B*, 22, 2640 (2004).



(a) (b)

Figure 1 (a) Scanning electron micrograph of PhC waveguides (b) experiment measurement (unfilled-symbols) and FDTD simulation results (filled-symbols) for crosstalk.

Silicon Double-Inversion of Polymeric Templates: A New Route Towards Three-Dimensional Photonic Bandgap Materials

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We present the successful silicon double-inversion of three-dimensional polymeric templates for Photonic Crystals. In a first step, the high-quality polymer template [1] is infiltrated via a room temperature silica chemical vapor deposition (CVD) process. Plasma etching and thermal combustion subsequently remove the original polymer template.

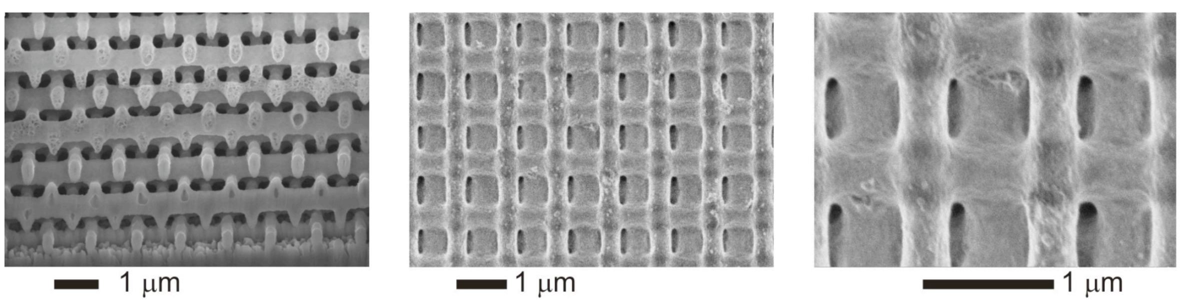

Fig. 1. SEM micrographs of the final silicon structure: (left) A cross section obtained with FIB slicing, clearly showing three-dimensionality of the final structure. Inhomogeneities are due to a slightly tilted slicing plane. (center) Top view of the silicon woodpile. The lattice period of the original template is well preserved. (right) Magnification of the surface. Note that even small features resulting from the resolution of the photoresist are well reproduced in our approach.

In a second step, the silica template is infiltrated with silicon via Si-CVD with disilane as a precursor. The silica backbone is finally removed by wet chemical etching, leaving behind a replica of the original polymer template cast in silicon (see Fig. 1). In combination with plasma treatment [2] of the original template, our method opens a facile way for the production of large-scale functional 3D Photonic Crystals at telecommunication wavelengths.

[1] M. Deubel et al., Nature Materials **3**, 444 (2004)
[2] G. von Freymann et al., Photonics and Nanostructures **2**, 191 (2004)

3D Photonic structures fabricated by Focused Ion Beam milling

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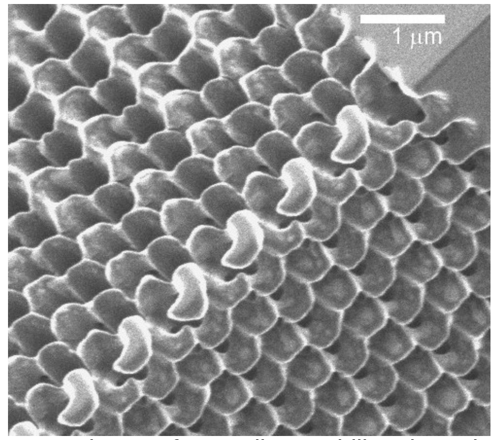
[1]Complex Photonic Systems group, [2]Optical Techniques group
MESA+ Research Institute, university of Twente, Enschede, The Netherlands

Photonic crystals with a diamond structure are exciting structures since they are predicted to have a large photonic band gap. We present a new way to make these structures by using a versatile Focused Ion Beam (FIB). A pattern of pores with a diameter of 400 nm was milled in two perpendicular directions in a gallium phosphide wafer. A diamond-like structure of interconnected pores was made in this way (see figure). The correct alignment of the pores is crucial in obtaining a true diamond-like structure. We discuss means to solve this problem.



SEM-picture of a 3D diamond-like photonic structure realized using FIB. The structure is 16 layers thick, which is twice the thickness realized elsewhere.

Nonlinear Wave Interaction Processes In Photonic Band Gap Materials

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Photonic Band Gap (PBG) materials attract much interest, since they allow one to control the flow of light on a level unachievable before. Employing the nonlinear properties of such systems brings about fascinating opportunities for shaping and manipulating optical pulses. For instance, in nonlinear PBG materials, there exists a novel class of localized excitations, the so-called gap solitons, whose frequency content may lie within the photonic band gap. In addition, gap solitons may have zero group velocities. Nonlinear wave interaction processes provide efficient mechanisms for dynamically controlling these optical waves. Here, we examine, both analytically and numerically, the interaction of nonlinear waves in one-dimensional photonic band gap materials. In the limit when the nonlinear Schrödinger equation is a valid model the analytical formulae determine accurately the phase shift experienced by nonlinear waves during non-resonant interaction. For the more complex cases of non-elastic wave interactions or soliton-defect interactions we present the comprehensive numerical studies.

Waveguides in Pillar Photonic Crystals for Integrated Optical Buffers

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A new structure of pillar PC is suitable for optical buffers, which are needed for routing photonic packets in photonic network. The delay time for a 5×5-mm pillar-PC chip would be several tens of nanoseconds.

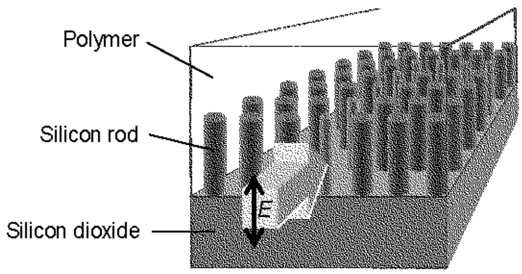

Fig. 1: Schematic of pillar PC.

Figure 1 shows the structure of new pillar PC with a bent line-defect. A calculated dispersion relation showed that a guided mode ranged from λ =1525 nm to λ =1603 nm ($\Delta\lambda$ = 78 nm) for a lattice constant a = 0.43 μm. A group velocity of guided light was measured with a fabricated sample and was found to range from 0.1c to 0.2c, where c is the speed of light in a vacuum. Also, our 3D-FDTD simulation revealed that a 90° bend of the waveguide efficiently transmits light over a wavelength range of 60 nm. Combining the small group velocity and the compact folding of waveguide using 90° bends would enable a 5×5-mm PC chip of pillar PC waveguide to produce a delay time of several tens of nanoseconds.

This work was partly supported by the Ministry of Public Management, Home Affairs, Posts and Telecommunications (MPHPT).

Light transport in complex photonic systems

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We will give an overview of various light transport phenomena in one dimensional photonic structures, focusing on ordered structures in which the periodicity is broken.

Fibonacci quasi-crystals are non periodic deterministic systems that present long range correlations. We investigate, using time-resolved transmission experiments, their rich fractal structure. The transmission spectrum exhibits narrow peaks associated to localized modes, alternated with forbidden frequency regions or bandgaps [1].

Also we will report on periodic structures in which a linear gradient is imposed on the refractive index. This constitutes the optical analogue of an electronic crystal on which a static electric field is applied. The refractive index gradient mimics the static electric field and allows to study two well-known electron transport phenomena, Bloch oscillations [2] and Zener tunneling [3], for optical waves. We report on the experimental and numerical study of these effects in optical superlattice structures.

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[2] R.Sapienza, P.Costantino, D.S.Wiersma, M.Ghulinyan, C.J.Oton, and L.Pavesi, *Phys.Rev.Lett.*, **91**, 263902 (2003)

[3] M.Ghulinyan, C.J.Oton, Z.Gaburro, L.Pavesi, C.Toninelli, and D.S.Wiersma, to be published

Large-scale three-dimensional microstructures based on macroporous silicon

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Three-dimensional (3D) nano- and microstructures have been fabricated up to now by using mainly colloidal self-assembly and the so-called *layer-by-layer technique*, i.e. the structure is grown by depositing and patterning successive layers, or bonding various single-layer structures together. Another approach of creating perfect 3D microstructures is the formation of macropores in silicon by electrochemical etching. In this work we report on the fabrication of 3D microstructures, which are possible candidates for applications as 3D photonic crystals. In the photo-electrochemical etching, macropores of an arbitrary pattern can be formed by lithographically pre-structuring of silicon. The resulting structure is a 2D lattice of well-ordered macropores. The pore diameter is mainly determined by the applied etching current, which itself is adjusted by the backside illumination intensity. In this way, the periodicity parallel to the pore axis (third dimension) can be independently controlled from the periodicity perpendicular to it. This gives us a freedom to choose the current profile and thus, to modulate the pore diameter accordingly. We have fabricated structures with symmetric and asymmetric variation of pore diameter in depth. We show that with a little additional work the fabricated microstructures can be converted into fully 3D networks of interconnected voids (Fig. 1). The current can be controlled in such a way that different plane defects can be integrated in the structure. These defects could act as planar waveguides or resonator structures.

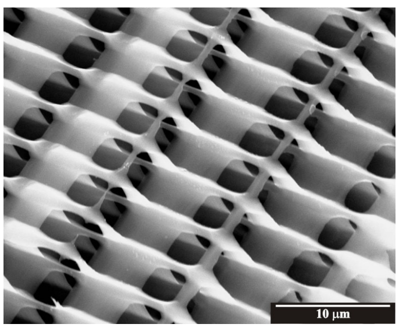

Fig.1. A fully 3D network of interconnected voids in silicon

Design of Optical Filter in Rod-type Photonic Crystal Slab

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We present a design of an optical filter to realize an optical add-drop multiplexer by using a rod-type photonic crystal (PC) slab. The structure of an optical filter in a rod-type PC slab is shown in Fig.1. The PC slab consists of square lattice of Si rods embedded in polymer layer and an underlying SiO_2 layer. In order to form an optical filter, a row of the rods is replaced by a Si channel with a rectangular crosssection.

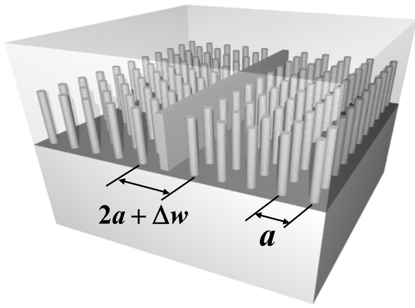

Fig.1: Structure of Optical Filter

According to our dispersion relation calculations, a wide interval between neighboring rods ($2a + \Delta w$) results in a small stop band because the influence of the periodicity of the PC to waveguide modes becomes small. $\Delta w \geq a$ is required for a stop band smaller than 1nm.

This work was partly supported by the Ministry of Internal Affairs and Communications (MIC).

Membrane-type DBR-microlasers for the integration of electronic and photonic ICs

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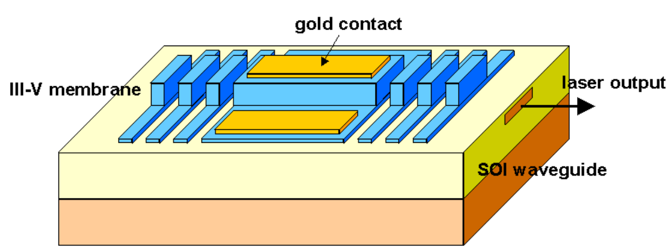
For future electronic integrated circuits, a severe bottleneck is expected on the global interconnect level. An optical link that consists of a laser source, an optical waveguide and a detector, integrated with the microelectronic circuit, can prove to be a solution. A promising approach for a compact optical link is the use of a Silicon-on-Insulator (SOI) waveguiding layer in combination with III-V microlaser sources and microdetectors, which are defined in a III-V membrane layer bonded on top of the SOI-stack [1].

In this paper, we focus on the design of electrically pumped membrane-type DBR-microlasers that couple evanescently to a passive SOI-waveguide. We have performed a two-dimensional eigenmode expansion analysis of these DBR-microlasers, including metal contact absorption losses, semiconductor absorption losses and diffraction losses. The results show that an optimized, 25um-long device in a 1um-thick membrane supports laser modes with a threshold material gain level comparable to gain levels for long-wavelength VCSELs [2], i.e. around 1000/cm for 4 quantum wells. For these devices, almost 30% of the total cavity losses are coupled to the SOI-waveguide. The fabrication scheme of the device is compatible with current state-of-the-art processes.



[1] C. Monat et al., *Electron. Lett.*, **37**, pp. 764-765 (2004).
[2] I. B. Dubravko et al., *IEEE J. Quant. Electron.*, **37**, pp. 764-765 (2004).

Fabrication of photonic crystals in InP by Cl2-based inductively coupled plasma etching using sidewall passivation

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Deep etching of two-dimensional photonic crystals in InP-based planar waveguides has been performed by state-of-the-art techniques as chemically assi (CAIBE) [1] and inductively coupled plasma (ICP) etching [2], the latter being more suitable for large scale production. We present new sidewall passivation processes in Cl2-based ICP-etching to obtain holes with straight and vertical sidewalls. With this technique we are able to etch holes with a diameter of ~240 nm down to a depth of 3.4 µm, the shape being nearly cylindrical in the upper 2.5 µm, see fig 1.

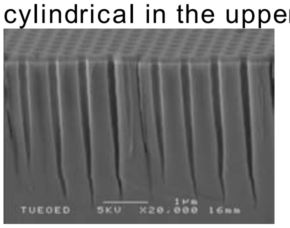

Figure 1: SEM view of the etched holes.

[1] M.V. Kotlyar *et.al.* , *Appl. Phys. Let.* **84**, 3588, 2004; M. Mulot *et. al.*, *J. Vac. Sci. Technol. B* **22**, 707, 2004.

[2] F. Pommereau *et. al.*, *J. Appl. Phys.* **95**, 2242, 2004.

Structural interface polariton modes

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The appearance of localized polariton modes at the interface separating two dielectric media requires the formation of electromagnetic evanescent waves on each side of the interface, supplemented by wave-vector dependent, incidental, conditions relating the dielectric constants of both media. At the junction of homogeneous materials, this sets very stringent requirements which can only be met by dispersive materials in narrow frequency ranges. These include infrared polar dielectrics with phonon polaritons and metallo-dielectric interfaces with plasmon polaritons [1].

When homogeneous media are replaced by structurated interfacial metamaterials, the appearance of localized modes depends on very different conditions. Evanescent waves can arise from multiple reflections on the metamaterial interfaces and the boundary matching at the junction of metamaterials can also be tuned by a structuration of the connecting layer. This communication will investigate several examples of structural interface polaritons, i.e. polaritons arising from the spatial structuration of metamaterials. The possibility of their study via attenuated total reflection or electron energy-loss experiments will be discussed.

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Novel application of photonic crystals - Optical Isolation for Electrical Contacts

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Placement of electrical contacts that only minimally disrupt the optical signal is a key design consideration for electro-optical devices. This becomes increasingly difficult for high index contrast systems such as Silicon-on-Insulator (SOI) with optical modes highly confined to cross-sections as small as ~ $0.1 um^2$.

We demonstrate an effective method of contacting SOI slab PhC waveguides that achieves effective electrical connection while minimizing optical losses. Metallic contacts are placed laterally 4 rows from the waveguide channel. Here the optical field is attenuated by the PhC lattice by almost 50dB compared to the center of the channel providing excellent optical isolation. Optical transmission measurements performed on PhC waveguides with heavily doped metallized ohmic lateral contacts show losses increased by only 5 dB/cm. The thermo-optic response of these devices was analyzed with the channel acting as a micro-heater. Thermal imaging (see Fig.) of the device showed that the "hot spot" is localized on a micron scale.

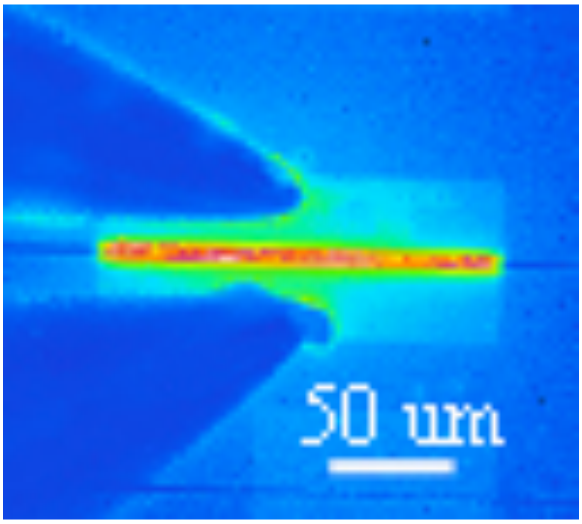

Fig.1 Thermal microscope image of the temperature distribution in PhC waveguide heated with lateral electrical contacts.

Acousto-optics effects in photonic crystals

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The effect of a time-varying modulation of the periodic potential of a photonic crystal is investigated. The theory rests on a recent description of the chirped photonic crystal modes in terms of energy carriers [1] accelerated by refractive index gradients.

The time-evolution of the scalar envelope function describing the photonic carrier dynamics is derived from time-dependent Maxwell's equations. Long-range, slowly-varying, refractive index changes caused by a high-intensity ultrasonic wave launched in a piezoelectric structure are assumed.

The theory is applied to a one-dimensional stack of "1-3" piezoelectric materials, with the "1" axis oriented perpendicular to the layers. A monochromatic incident light beam, polarized along the "3" axis is incident on the structure, resulting in "1"-axis mechanical compression. The transmission of this stack is studied for a range of frequencies which encompass a 1D stop-band. From these, the probability of absorption and emission of acoustic power, leading to photonic carrier interband transitions and a corresponding change of light frequency, is investigated. The possible use of these effects for the determination of electro-mechanical coupling coefficients is discussed.

[1] V. Lousse and J.P. Vigneron, this conference.

Control of colloidal crystal growth by external fields

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Since the introduction of the concept of a photonic crystal much effort has been targeted at producing 3D photonic crystals working in the visible wavelength range. The most promising way is by self-assembly of monodisperse sub-micron spheres made of silica or organic materials resulting in fcc and hcp colloidal crystals. However, the large scale fabrication and thus their application in photonics suffer from the reproducible growth of defect-free extended bulk crystals. Commonly used 'natural' sedimentation is unacceptably slow and often results in low crystal quality showing cracks and stacking faults or reveals a disordered bulk below an apparently ordered surface. In literature there are several examples, where additional external fields such as electric or acoustic fields were applied, which to a certain extent enhanced the crystal quality. However, the reproducibility of such experiments depends on many parameters like the chemical composition of the spheres, the solvent, the density ratio of spheres and solvent, and many more. To have control of all this parameters during crystal growth is one of our current projects. We will present details of our computer controlled crystal growth experiments using specific external fields. In classical crystal growth methods (e.g. Czochralski-growth), one avails of temperature gradients. In analogy, we use acoustic noise gradients instead of temperature gradients for optimizing crystal growth. The crystal growth and evaporation of the suspension is monitored by CCD-cameras and thus computer-controlled.

Engineering the electromagnetic vacuum for controlling light with light in a photonic bandgap micro-chip

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We consider electromagnetic vacuum density of states engineering in a 3D photonic bandgap material as a mechanism for providing low threshold, high speed nonlinear optical response. This provides an alternative to conventional all-optical switching schemes based on micro-cavity resonators with a Kerr-nonlinear response exhibiting the fundamental trade-off between switching time and switching threshold intensity. Our vacuum engineering involves a trimodal waveguide architecture in a 3D photonic bandgap material with a fork-like local electromagnetic density of states (LDOS). Two wave-guide modes increase the electromagnetic LDOS (near their cutoff frequencies) by a factor of 100 or more relative to the background LDOS of a third air-waveguide mode with nearly linear dispersion. Atoms in this "engineered vacuum" can be coherently pumped to a population inverted state, which can then be used to coherently amplify fast optical pulses propagating through the third waveguide mode. This nonlinear switching of atomic population occurs for pump power level on the scale of a micro-Watt. The resulting coherent "control of light with light" occurs without recourse to micro-cavity resonances (involving long cavity build-up and decay times for the optical field). Thus, enables rapid modulation (switching) of light.

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The effect of short-range order on the transmission property of 12-fold quasiperiodic photonic crystals

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Photonic band-gap material, since proposed by Yablonovitch and John, has attracted considerable attention. Great deal of theoretical and experimental effort has been devoted to study the properties of the material. Owing to the symmetry, the property of periodic photonic materials is very clear. The long-range translational and oriental order resulted from the periodicity of the photonic crystals plays an important role. Compared with periodic photonic crystals, only long-range oriental order exists in quasiperiodic photonic crystals. Does the long-range order resulted from quasiperiodicity have the same effect on the transmission properties of QPC as those in periodic photonic ones? Periodic photonic crystals can be considered constructed with basic cell or some kinds of supercells. Similarly, QPCs[1,2] also can be considered in the same way. Recently, we study the property of modified 12-fold quasiperiodic photonic crystals in which the supercells are arranged in various ways. The result shows that although the order of rotational symmetry, namely the oriental order, is reduced by arranging the supercells periodically, the transmission propertied remain almost unchanged.

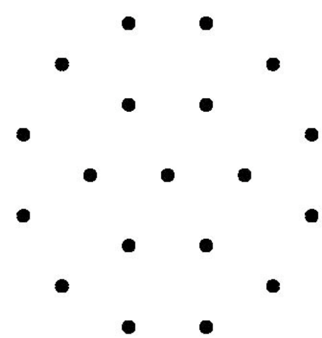

Fig. 1

The 12-fold QPC mentioned in ref. 1 is built up with dielectric cylinders placed on the vertices of random square-triangle tiling system. It can be considered constructed with supercells shown in Fig. 1. In the QPC, these supercells are arranged quasiperiodically. With the same supercell, two different crystals where the supercells are arranged in square and triangle periodic fashions are constructed and their transmission spectra show that the location and the width of the gaps are all identical with those of QPC shown in ref.1. Furthermore, the absolute gaps shown in the band gap structure display that the modified QPCs are also isotropic. It indicated that the order of rotational symmetry resulted from quasiperiodicty have little relation with the transmission property of the QPC. Fig. 1 Supercell of QPCs In order to identify which factor determines the properties of QPCs, transmittance of the supercell is calculated. The result shows that the gaps of the supercell are superposed with those of any kind of QPC. Therefore we can conclude that the local properties result in the isotropy in the QPCs.

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Simulation of group-velocity-dependent phase shift induced by refractive-index change in an air-bridge-type two-dimensional photonic crystal slab waveguide

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We present here a numerical analysis of the group velocity (*vg*) dependent phase shift induced by the small changes of the refractive index (Δn) in the 2D photonic crystal (PC) slab waveguide. The calculation was based on a 3D FDTD method for the design of a phase shift arm of the PC-based symmetric Mach-Zehnder (PC-SMZ) type all-optical switch. As shown in Fig. 1, Δn was assumed to be induced by an optical nonlinearity of quantum dots embedded in the phase shift arm. It was shown that the arm length necessary for the switch is significantly reduced because of the low *vg* in spite of the small Δn. For example, the arm length was evaluated to be ~100μm for Δn of ~0.001, *vg* of 0.03*c*, and a lattice constant of 0.36μm at a wavelength of ~1.3μm (*c* is light velocity). The resultant waveguide length is short enough to achieve a compact ultrafast all-optical switch.

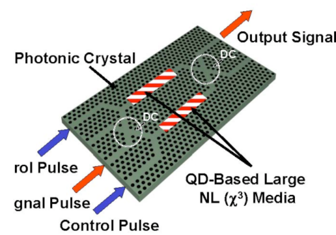

Fig. 1: Schematic of a PC-SMZ switch.

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Lithography Limits of Photonic Crystals

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The creation of high quality photonic crystals requires very demanding lithography. Accurately creating structures with the desired spectral response can be very challenging, especially for devices such as high-Q cavities [1]. The importance of disorder in photonic crystals is also very important [2]. It has recently been shown that losses in photonic crystal waveguides increase with increasing disorder [3]. The overall disorder may be considered to consist of positional disorder- due to variations in the hole spacing, and size disorder- due to variations in the hole size. Both of these largely originate in the initial lithography stage, (though subsequent processing steps are also important).

In this work, we look at the methods of minimising disorder and improving the general quality of two-dimensional photonic crystals through an improved understanding of electron beam lithography for pattern definition. The effects of the various machine parameters such as step size, digital resolution and beam drift and software related issues such as proximity correction are determined.

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Low loss two dimensional InP-based photonic crystal waveguides

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Two dimensional (2D) photonic crystals (PhCs) in InP-based materials are attractive candidates for applications in integrated circuits. For most applications reaching low losses in 2D PhC devices is one of the most important outstanding challenges to make them beneficial to integrated circuits. So far two types of 2D PhC are commonly investigated in literature: membrane type and low index contrast based structures. We will report on the optical characterization by an endfire technique of 2D PhC waveguides etched through an InP-based waveguide by inductively coupled plasma etching using $SiCl_4$ chemistry [1]. The PhC waveguides were either butt-coupled and/or coupled by a PhC-based taper to the ridge waveguide. The propagation losses of the PhC waveguides were determined by using Fourier analysis [2] of the transmission spectrum through PhC waveguides. Despite the small light absorption in the measured short W3 PhC waveguides
(*i.e*. 3 missing rows of holes in ΓK direction) an upper limit of propagation losses of 84 dB/cm was obtained. These values are amongst the lowest values reported on low index contrast based 2D PhC waveguides so far. Measurements on longer PhC waveguides will be presented to determine more precisely the propagation losses.

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Resonant field patterns in negative magnetic metamaterials

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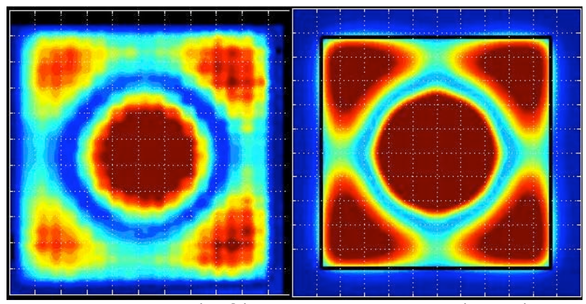
The “Swiss Roll” structure is an anisotropic magnetic metamaterial that has proved very suitable for the radio frequency (RF) regime. Treated as an effective medium, the permeability along the axis has a resonant form and exhibits negative values over a significant bandwidth (up to 40% has been achieved). When a prism of such material is excited by an RF magnetic field, it exhibits a complicated sequence of resonances. In this work, we examine whether an effective medium model can describe this behaviour.

The field distribution was measured by scanning a small loop detector above the surface of a square prism of Swiss Rolls, excited by a similar loop below the slab. Modeling was performed using MicroWave Studio, with permeability parameters derived from those measured for the material. Excellent agreement (see figure) over most of the negative permeability Range was obtained.



Measurred (left) and calculated (right) magnetic field distributions at 24.9MHz

Hybrid superprism with low insertion losses and suppressed cross talk

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Cross talk and high insertion losses are issues that need to be resolved to build efficient demultiplexers based on the superprism effect. Here we show that an adiabatic transition inside the photonic crystal (PC) can alleviate the insertion losses, provided the PC boundary is along a crystallographic axis that breaks certain symmetries. Bloch modes located at the sharp features of the equi-frequency contours (EFC) are the most useful for light demultiplexion, but have a complex structure that is difficult to couple to. Inside the adiabatic transition they are projected onto other regions of the EFC that do not feature such difficulties. In this way more than 90% insertion efficiency is demonstrated with 2D FDTD.

Furthermore, beam broadening inside the PC limits the resolution of superprisms. We show that positive refraction in the material prior to the PC can compensate negative refraction inside the PC so that refocused beams are obtained at the output edge of the crystal. In such a way beam broadening inside the PC is compensated and cross talk is suppressed. 60 nm resolution is obtained with a 27 μm wide PC (2D FDTD). The resolution is shown to scale directly with the size of the PC *in this design*.

Focused Ion Beam milling of nano-boxes in self-assembled opal photonic crystals

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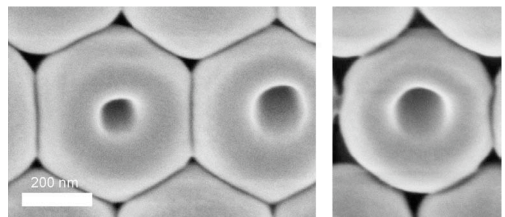
Point defects in 3D photonic crystals are of great interest due to their ability to act as a cavity that localizes photons. Since the mode volume of such a cavity is predicted to be smaller than a wavelength cubed, they are called nano-boxes. We present a method to fabricate controlled point defects in self-assembled opal photonic crystals. The defects are milled with a focused ion beam at the surface of an opal, see figure, and then buried by additional crystal layers. We can control the size and shape of the defects by changing the milling parameters. We will discuss a route to obtain cavities in inverse opals, using our new results.



SEM picture of defects milled with a FIB. The scale bar equals 200 nm.

Wavelength selective coupler based on Bragg Reflection Waveguide

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Highly wavelength selective optical filters are essential components for channel management in modern Dense Wavelength Division Multiplexed communication systems with 50GHz channel spacing and below 0.4nm channel bandwidth. We have designed, fabricated and characterized a new type of wavelength selective directional coupler, based on the high differential dispersion between a Bragg Reflection Waveguide (BRW) and a conventional buried channel silica waveguide. The bandwidth of the device is inversely proportional to the length of the coupler as well as to the differential effective refractive index dispersion of the coupled modal fields, at the wavelength of phase matching. The BRW is made of a high index (amorphous) silicon core layer, surrounded vertically by two periodic Bragg reflectors with alternating layers of silica and silicon. The silica waveguide with a Ge-doped core, vertically stacked with the BRW, allows fiber incoupling loss below 1dB which is essentially the insertion loss of the device. The device is operating within the optical bandgap of the Bragg reflectors. Both the bandwidth and the coupling wavelength can be tuned during the fabrication process: the fields' overlap and the coupling coefficient between the two waveguide modes are controlled by one of the Bragg reflectors (coarse control) and a spacer layer (fine control); the position of the coupling wavelength is mainly determined by the BRW core thickness. The devices were fabricated by depositing SiO_2 and a-Si:H films on a 4" <100> oriented Si substrate, by plasma enhanced chemical vapor deposition, at a temperature of 250ºC. The 5µm wide vertical stack of BRW and silica waveguide were defined by lithography and etched in an inductively coupled plasma reactor. The 8.8µm thick coupler structure was covered with a 16µm thick silica cladding. The device can be easily integrated in a standard silica-based planar lightwave circuit. The measured filter suppression is 14dB and the FWHM is 0.29nm for only a 1.73mm long device, which is close to the estimated value of 0.31nm, and one of the lowest ever reported for this type of coupler.

Fabrication of Photonic Crystals Using Single Refracting Prism Holographic Lithography

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As being able to produce defect-free, nanometer-scale structures over large area uniform PhCs in a single step fabrication, holographic lithography has shown to be a very economy and powerful tool and might hold the key to volume producing of photonic structures. In the previous demonstrations, however, multiple beams forming the interference pattern were obtained by two independent optical elements and steps: splitting the laser output into multiple beams either by a dielectric beam splitter or a grating; and then superposing them at the exposure area by another specially designed prism. This fabrication strategy can introduce alignment complexity and inaccuracies due to differences in the optical path length and angles among the interfering beams as well as vibrational instabilities in the optical setup. We now demonstrate another approach for easy fabrication of 2D and 3D photonic crystal microstructures, based on beam splitting and overlapping by a single refracting prism. 3- and 4-beam interference pattern is generated and recorded in a photosensitive polymer. This method enables splitting of an incoming laser beam into multiple beams and at the same time, recombining them by the same optical element. Thus, anti-vibration equipment and complicated optical alignment system to adjust the angles between the interfering beams are not required, leading to a very simple optical setup. Temporal overlap of the divided pulses will be able to be achieved without adjusting the optical path lengths if a pulsed laser to be applied in the fabrication. In the context of mass production, this method is much more practical and robust than those previous demonstrations by two independent-element setups.

Dual lattice photonic-crystal beam splitter

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Light propagation in photonic crystals (PhCs) is both sensitive to incident angle and wavelength. By combining two different PhC lattices, we utilise this effect to demonstrate a wavelength-dependent beam splitter with enhanced angular separation. The first lattice (250nm) belongs to branch 1 acts as a superprism that separates the incoming light according to wavelength (Fig. 1a), whereas the second lattice (420nm) in branch 3 acts as an angular amplifier (Fig. 1b). We obtain 90^o angular separation (Fig. 3) for two wavelengths separated by 70 nm (1300 nm regime) in a structure that is less than 10 μm long.

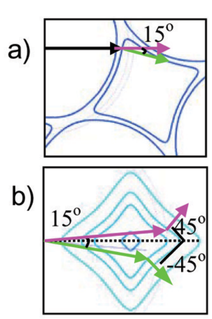

Fig. 1 a) Equi-frequency Contours (EFCs) for branch 1; b) EFCs for branch 3

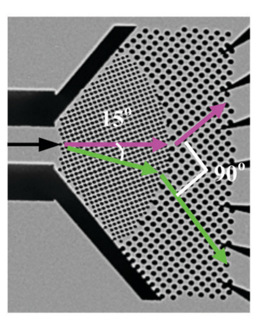

Fig. 2 SEM (top view) of PhCs with input and output waveguides

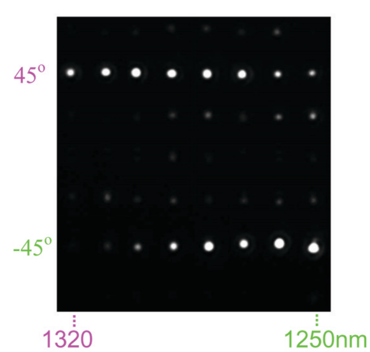

Fig. 3 Vidicon micrographs of the output facets as a function of wavelength.

High transmission through waveguide bends by use of a circular photonic crystal

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Photonic Crystals (PCs) have received considerable attention owing to their abilities for the realization of ultra-compact and multi-functional devices for high-density photonic integrated circuits (PICs). It is necessary to introduce waveguide bends for the high-density, which become one of the main contributions in not only generating loss but also limiting the bandwidth of the transmitted signal. Various alternative approaches for bend designs have been theoretically or experimentally studied [1-3].

In this paper, we design PC waveguide bends by use of a matched circular photonic crystal (CPC) and demonstrate it to improve the transmission properties of waveguide bends in a 2D photonic crystal. The 2D photonic crystal considered here is a triangular lattice of air holes in a dielectric media. A circular photonic crystal connects the 2D PC waveguides instead of conventional PC waveguide bends. The structure of the CPC follows the rule that the distance between holes must be constant on each concentric circle. The air holes are arranged in the form of concentric circles with radial distance d. The positions of the air holes for a sixfold symmetric CPC are given by

$$x = dN\sin(2m\pi/6N),\; y = dN\cos(2m\pi/6N)$$

where N, d and m are the number of concentric circles, the radial distance, and an integer from 1 to $6N$, respectively.

We have studied two types (Y and U type) of PC waveguide bends utilizing CPCs. It has been shown, compared with conventional PC waveguide bends, that the bend losses of our designs are much smaller. The bend losses are less than 1dB over a relative 8% bandwidth. Further study for optimizations are still in the progress. Theoretically, an arbitrary bent angle of a line-defect waveguide can be designed by use of the CPC.

This work was supported by the Swedish Foundation for Strategic Research (SSF) INGVAR program, the SSF research center on Photonics and the Swedish Research Council (VR) under project 2003-5501.

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Phononic band calculation by PWE including evanescent waves

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The method of PWE is always used to calculate the band structure of phononic crystals, while the wave number in this method is often confined as real number, which represents only the modes of traveling waves in the pass band. An improvement has been proposed which makes the results of the method includes traveling wave modes and evanescent wave modes, in pass bands and forbidden bands respectively.

The idea is based on the fact that the evanescent mode exists in forbidden band and it’s modulus decay is ω the imaginary part of the wave number[1][2]. Therefore, in the original eigenvalue equation for , the value of ω wave number would extend to complex number space, and the must be real when the wave number represents an evanescent mode in forbidden band. The developed method is very simple and accurate to calculate all the modes in a phononic crystal, and also the transmittivity, reflectivity and branching ratio. Ω Comparing with the FDTD method, the dependence is not a serious factor for numerical calculation, and there are not problems of unphysical results derived from numerical unstableness.

As a test, we have calculated the band structure including evanescent waves for a square lattice with cylindrical inclusions, and very smooth curves of modulus decay are obtained in forbidden band, which have shown no sign of numerical unstableness. For Bragg scattering, no matter the variety of geometry of the lattice and scatters, the curves have shown bilateral symmetry about the center of the forbidden band, and the maximum of the modulus decay is increasing with the width of the forbidden band. At the edges of forbidden ω bands, the changes of the modulus decay with are abrupt in the curves of FDTD, while they are relatively smooth in that of our developed PWE and in the emulation results of MSC software. The more details of the very developed PWE need to be checked in future work.

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A Hung-like model of local resonance in two dimensional phononic crystal

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A new area of research has been opened in the field of phononic crystals since the recent work of Liu et al. [1] who, based on the idea of localized resonant structures, demonstrated the existence of spectral gaps at extremely low frequencies (2 orders of magnitude smaller than the Bragg frequency associated to the lattice constant). It makes such a composite an interesting material for blocking low frequency sound. Such an effect is manifest in the electromagnetic frequency response of ionic crystal with optical vibration, which is described by Huang Equation. In our work, an analytic Hung-like model is proposed to describe the physical insight of local resonance, that is the scattering due to the coupling between vibrations of the microstructure and the long-wavelength elastic waves.

An SH wave scattering problem was considered for a hard circular cylinder coated with a soft cladding and embedded in a linearly elastic medium of infinite extent[2]. The scattering cross section and the field distribution were analysised. From the peaks in the dependence of scattering cross section on ω, intensive scattering phenomenon were observered at the resonant frequencies of the microstructure, where the size of the scatterers were much smaller than the wavelength of the incident wave. The position of those peaks were consistent with the bottom of the spectral gaps at low frequencies. The abnormal disperse relation and negative effective elastic constants were also obtained from the Hung-like model, and the relations were discussed between the field distributions of the diffusion and the localized resonant behaviors. The results were compared with previous studies [3] and were agree well.

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Group Velocity Reduction through Line Defect Photonic Crystal Waveguide

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Photonic crystal (PhC) waveguides offer unique dispersion properties, i.e. low group-velocity and extremely high Group Velocity Dispersion. These properties may in turn enable optical delay lines and optical pulse compression/dilation. This work investigates the group delay (GD) through a 80 μm long single-line defect PhC waveguides fabricated using E-beam lithography and RIE etching. The TE mode gap beginning at ~1534 nm, was confirmed by transmission measurements using a TE polarized input. Group delay was investigated using swept wavelength interferometry and the Jones matrix method. The average GD of the two eigenstates of polarization shows a dramatic increase near the band edge compared with a reference waveguide. The Differential Group Delay (DGD), the difference between the delays of the two polarization eigenstates, was observed to be as much as 30ps near the edge of the mode gap through the PhC waveguide. This is believed to be due to the slow light transmission of the TE mode at a largely reduced group velocity near the edge of the mode gap, which corresponds to a group velocity for the TE modes less than 0.01c.

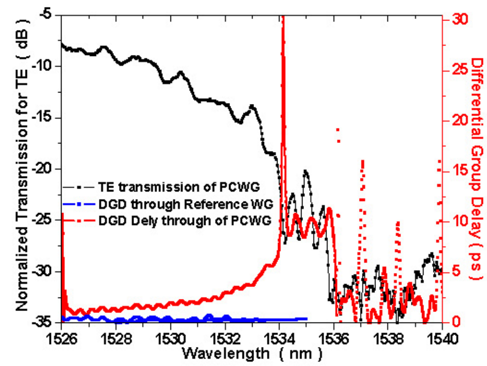

Fig.1 Transmission spectrum with TE polarized input (left axis) and Differential Group Delay (right axis) through a 80 μm single-line-defect PhC waveguide

Dual wavelength low group velocity Photonic Crystal for resonantly pumped

surface emitting lasers

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Two-dimensional Photonic Crystals (2DPCs) are ideal objects for fabricating micrometer-sized laser sources. Until now the main effort has been devoted to achieving high Q cavities or low group velocity modes at the lasing wavelength. But 2D periodicity gives *sophisticated* means of engineering the photonic modes. Capitalising on this, we designed and operated a dual wavelength laser structure which exhibits a low group velocity mode *both* at the lasing and the optical pumping frequencies. As a further sophistication we fabricated an InP-based two-dimensional photonic crystal slab laser with a photonic mode lying in the bound quantum well electronic level. The pump and lasing modes are separated by just one Longitudinal Optical phonon energy, in order to minimize thermal effects. Laser operation is demonstrated at 1566 nm in the pulsed regime. A threshold of $4kW/cm^2$ is obtained. With respect to the usual method of high energy optical pumping, which involves the creation of carriers in high electronic levels, our laser shows a 10 fold improvement.

Intertwined carrier and field dynamics in 2D semiconductor photonic crystals

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One of the particularities of semiconductor 2D Photonic Crystals (2D PC) is the presence of high Q resonances corresponding to low group velocity modes at the band edge[1]. This gives photon lifetimes which are fairlly long, of the order of a few picosecond. Moreover, in semiconductor 2D PC structures with hole lattice the carrier relaxation time is shorter than in the bulk material due to the faster recombination time in the air/semiconductor interfaces. The combination of these two features results in the photon lifetime within the resonator becoming non-negligeable with respect to the carrier relaxation time. Under these conditions the carrier dynamics is expected to affect the field evolution within the resonator when the two relax freely. In this work we put into evidence the subtle interplay between the carriers and field in the time scale of the photon lifetime by means of femto second pump and probe experiments.
We show that for pump-probe time delays of the order of the photon lifetime, the reflected probe signal manifests spectral oscillations as the system is pumped close to laser threshold. We link these oscillations to the frequency chirp due to fast carrier recombination in the early stages just after the arrival of the pumping pulse. An accurate theoretical analysis based on mean-field equation for slowly varying amplitude of the elctric field coupled with the carrier evolution equation describes the complex system closely and allows us to extract relevant parameters related to the material and photonic confinement.

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Amplification in 2D Photonic Crystals

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Recently, many optical nonlinear functionalities have been demonstrated on two dimensional photonic crystals (2DPC), such as laser operation, wavelength tuning and fast switching [1,2]. In this work we demonstrate for the first time optical amplification in a InP-based 2DPC. We achieve an on/off gain of 27dB at 1.56 µm for a mean pump intensity of 4 KW/cm^2. Since the gain is probed quite far from the electronic band gap (~50 nm far in the Urbach tail), the simple passage gain is low. The key feature to obtain appreciable amplification is then the degree of light confinement into the structure provided by a high Q band-edge photonic resonance. As a consequence, the total gain is increased by a factor equal to the local intensity enhancement in the resonator with respect to the single passage gain. One of the particularities of our system with respect to other 2D geometrical configurations (such as cavities of the defect type), which could achieve the same degree of light confinement, is the possibility of coupling light into the resonator through radiative modes in the normal direction with respect to the periodicity direction. Engineering the finesse of the photonic resonance, as well as its position with respect to the semiconductor band gap, offers a high degree of flexibility in designing optimal amplification parameters for single or broad band amplification, an issue that will be discussed during the talk.

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Thermo-optic switch based on silicon photonic crystal waveguides

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A Mach-Zehnder(MZ) interferometer type thermo-optic switch based on silicon 2-dimensional photonic crystal (PhC) slab waveguide was demonstrated. The device consists of two PhC W1-line-defect waveguides connecting with Y-splitters made of silicon-wire waveguides. The PhC structure was specially designed with vertically symmetric upper and lower silica cladding layers. The device area size is 160 x 65 μm^2, excluding the heater electrode pads. The switching operation was realized by thermally controlling the refractive Index of one PhC waveguide of the MZ interferometer. At 1550-nm wavelength, more than 30 dB of extinction ratio was obtained at 120-mW heating power. The optic switching on/off response speeds were both about 120 μs. The switching bandwidth was more than 15 nm, when the extinction ration was over 30 dB. This work was supported by IT Prog,. MEXT and Photonic Network Proj., NEDO.

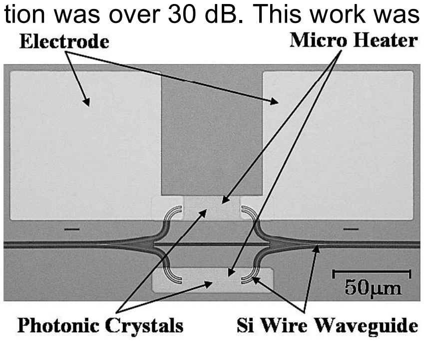

Fig.1:PhC thermo-optic switch.

Novel Fabrication Method for Semiconductor 3D Photonic Crystal

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We have investigated the 3D-PC waveguide system[1,2]. This time, we show a novel fabrication method for semiconductor three-dimensional photonic crystal shown in Fig. 1. This method is classified into one of the layer-by-layer methods. Such methods demand some methods to keep relative positions between each layer. In our method, registration exposure function, which is furnished with EB lithography, stepper and other lithographic system, is utilized to do it. Thus, no special alignment equipment is necessary. And a period of stacking direction is guaranteed by utilizing epitaxial wafer at step (ii).

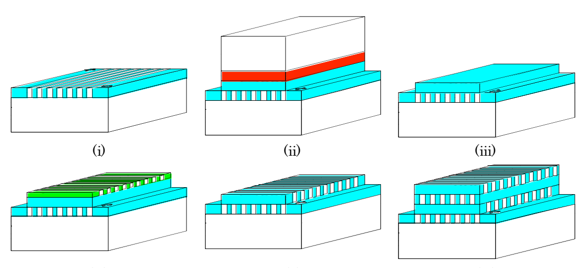

Fig. 1:Schematics of fabrication method of three-diemnsional photonic crystal. (i) 2D pattern fabrication, (ii) wafer bonding (iii) selective etching, (iv) registration exposure, (v) pattern transfer, (vi) repeat of former steps.

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Directional Coupler Switch -Small Coupling Length, High Extinction Ratio, Small Switching Length and Wide Bandwidth-

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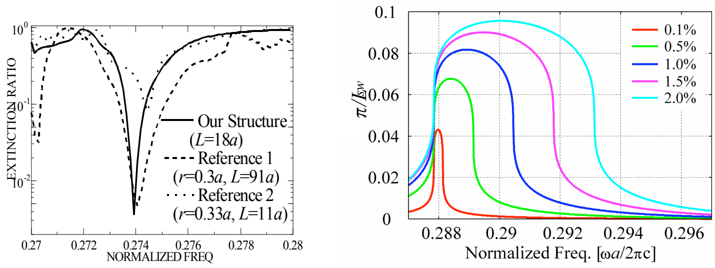

Fig. 1: Extinction ratios and switching length.

Directional couplers and switches based on them are important device to realize optical integrated circuit. The important parameters of them are coupling length, extinction ratio, switching length and bandwidth. However, it is hard to improve them simultaneously because they have trade-off relations. We develop novel directional structures to break these trade-off relations[1,2]. By numerical calculation, we obtained the DC with the coupling length of 18a and the extinction ratio of -24.4dB and the DC-switch with a switching length of 12a even if the refractive index change is 0.1%.

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Vertically-coupled Fano resonance in photonic crystal coupled cavity array

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In general, the Fano resonance is hard to be excited using normally-incident photons, because of the symmetry mismatch. In order to enhance the Fano resonance, we propose a photonic crystal coupled cavity array (PC CCA) made of triangular lattice air holes. This structure supports a mode that has symmetry properties reminiscent of those of the single-cell dipole mode. In addition, this mode localized near Γ point has small group velocity and desirable vertical radiation characteristics. To enhance vertical coupling, air holes of each cavity were slightly modified.

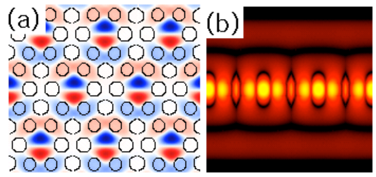

Fig. 1 Dipole mode in modified PC CCA slab. (a) Hz field at the center of slab. (b) Intensity profile at the vertical direction (logarithm scale).

Reflection and transmission characteristics were investigated by periodic finite-difference time-domain methods. The Fano resonance shows strong polarization dependence because of its inherent dipole-like electric field profiles.

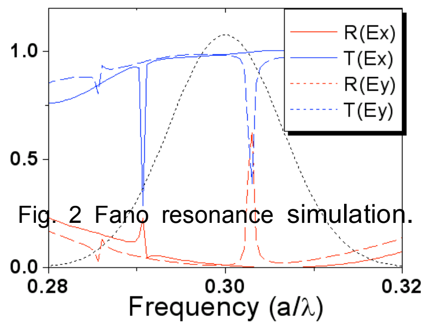

Fig. 2 Fano resonance simulation.

Instability, patterns and localized structures in photonic crystal thin films

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We consider a system in which a nonlinear photonic crystal film is irradiated from the top by a laser beam [1]. Under some conditions this system can be considered as two subsets of interacting nonlinear planar resonators. In this case the system can be described by the system of equations:

$$\partial_t U_{n,m} = -f(|U_{n,m}|)U_{n,m} + is_1(V_{n,m} - U_{n,m}) + is_2(V_{n-1,m+1} - U_{n,m}) + \\ + ir_1(V_{n,m+1} - U_{n,m}) + ir_2(V_{n-1,m} - U_{n,m}) + U_p$$

$$\partial_t V_{n,m} = -f(|V_{n,m}|)V_{n,m} + is_1(U_{n,m} - V_{n,m}) + is_2(U_{n+1,m-1} - V_{n,m}) + \\ + ir_1(U_{n,m-1} - V_{n,m}) + ir_2(U_{n+1,m} - V_{n,m}) + U_p,$$

where indices n,m mark resonators, $U_{n,m}$ and $V_{n,m}$ are the amplitudes of the fields in the resonators, f describes the nonlinearity which depends on the intensity, $s_{1,2}$ and $r_{1,2}$ account for the coupling between the resonators, and $U_p = U\exp(idt)$ is the pump field, where d is the pump frequency detuning.

We show analytically that this system exhibits modulation instability that can be stabilized for some ranges of detuning provided the dispersion characteristic has a sufficiently wide band gap. For the cases of Kerr and dissipative nonlinearities, it is shown by numerical simulation that the instability can lead to the formation of various patterns. Localized structures of light are also found.

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Variational Principle in Photonic Crystals: analysis and predictions

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Photonic Crystals (PhC) are promising structures capable to show a Photonic Band Gap (PBG). This means that light with particular frequency cannot propagate through the PhC no matter what direction or polarization. This peculiarity is due to the refractive index periodicity present in the photonic crystal. A lot of applications and phenomena can be thought thanks to PhC: band-filters, resonant cavity[1], laser without inversion, spontaneous emission[2], planar antennas[3] and so on. According to the application, both 2D and 3D photonic crystals can be involved.
Unfortunately so far it was not possible to realize any applications with three dimensional PhC with any kind of technique. In the case of two photons lithography, for example, it is because of the low refractive index present in photoresist materials (around 1.5/1.6). It is, indeed, one of the fundamental parameters that play a key role to obtain a full band gap. Our intention is then to find out which are the theoretical relations between the geometry of the device (i.e., symmetries), the minimum refractive index request and the possibility to have a full band gap. One first step in such direction is to investigate on the relations between band gap and intensity light distribution inside the lattice by means of the Electromagnetic Variational Principle. In particular we are going to analyze the Diamond structure because of its unique characteristic to be very unique to realize band gap even with very low refractive index ratio. We'll present the behaviour shown by the dispersion relation of a diamond lattice when the refractive index is changed, and we'll explain it thanks to the Variational Principle. Then we'll make some prediction on the characteristic that an ideal structure should have to maximize the band gap.

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Geometric freedom for constructing variable size photonic bandgap structures

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In order to study the design flexibility of photonic bandgap structures we investigate different examples of 1D, 2D and 3D structures as traditional Bragg layers, 2D photonic crystals, and 3D woodpile structures. It turns out that in systems with large gaps evanescent waves penetrate into the bulk only distances comparable to one lattice constant, therefore confinement of light can also be achieved *without*long range order, which leads to the introduction of novel photonic band gap designs. Adhering to some constraints the changes in the photonic band gap in disordered structures are negligible. The important quantity to characterize the presence respectively absence of modes is the local photonic density of states, however band gap phenomena in size and position disordered arrangements can also be verified with plane wave supercell calculations as well as finite difference time domain techniques.

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Organic 2D PC optical switching with picosecond response

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An all-optical switching with high switch efficiency is realized in terms of the shift of photonic gap edge under ultrafast optical excitation in a two dimensional nonlinear photonic crystal made of polystyrene, which is composed of regular square arrays of cylindrical air holes in 300 nm polystyrene film and prepared by using the focused ion beam etching system. The lattice constant and radius of air hole are 220nm and 90nm, respectively. The prism-film coupling method (with the help of evanescent fields) is used to couple energy of probe light into photonic crystal waveguide and a pump and probe method was applied to measure the transmittance of the probe light. High transmittance contrast of more than 60% is realized for the probe light at two states of "on" and "off "of the switching. Time response of the optical switching is around 10ps, which may be limited by the laser duration. The dynamical shifts of photonic gap induced by pump light are measured and analyzed. The photonic gap shifts 10 nm under the excitation of 16.7GW/cm^2 pump intensity, which is in agreement with the theoretical predictions.

Absolute negative refraction and image of unpolarized electromagnetic wave

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The all-angle negative refraction (AANR) is generally very important to design a microsuperlens. However, it is usually absent from some two-dimensional (2D) photonic crystals(PCs). In this work, we first present a method to create and enlarge the AANR region by using insertion. For some 2D dielectric PC systems without the AANR, the AANR region can be created by adding a fraction of a metallic component to the center of each dielectric cylinder. At the same time, the AANR region can be enlarged by adjusting the size of the metal cylinder. Based on these, absolute negative refraction for *both* polarizations of electromagnetic wave has been found. Thus, the focusing and images of unpolarized light can be realized by such a two-dimensional photonic-crystal-based superlens. These focusing and images do not only exist in the near-field region. The non-near-field images, explicitly following the well-known wave-beam negative refraction law, have been demonstrated. In addition, the effects of interface, disorder and absorption on such far-field image in a two-dimensional photonic-crystal-based superlens have also been discussed.

A compact design of in-plane channel drop filter using degenerate modes in 2D photonic crystal slabs

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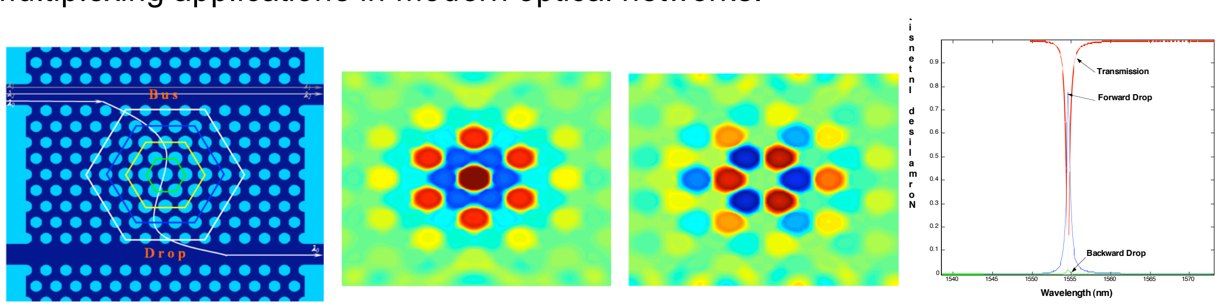
We have recently designed an in-plane channel drop in triangular-lattice 2D photonic crystal slabs. The system consists of two conventional waveguides and a cavity system. Three-dimensional finite difference time domain simulations have shown that the power transferred to the drop waveguide is 78% and only 1.6% is left in the bus waveguide. The quality factor is around 3,000. By tuning surrounding air holes, the light remaining in the bus waveguide can be further reduced to 0.3% at resonance.

The cavity is constructed by carefully arranging the radii of some periods of air holes into a graded pattern and involves no missing air holes [1]. This cavity supports two modes of opposite symmetry, one even with respect to the central plane perpendicular to the waveguides and the other odd. Since both modes remain even with respect to the central plane parallel to the waveguides, the transfer occurs along the forward direction of the drop waveguide [2]. The presence of Bus and Drop waveguides does not affect the vertical light confinement of the cavity and both modes keep high vertical Q values (>35,000). By tuning the radii properly, the two modes can achieve degeneracy with the same resonant wavelength. Moreover, both modes prove to couple equally into the waveguides and have similar coupling Q values (~3,000). Since the vertical Q is much larger than the coupling Q, the vertical loss of the system is kept low.

We believe this novel and compact design is adequate for dense wavelength division multiplexing applications in modern optical networks.



(a) (b) (c) (d)

Figure (a) top view of the system. (b) $\mathbf{H_z}$ field of the even mode at central slab plane. (c) $\mathbf{H_z}$ field of the odd mode at central slab plane. (d) intensity spectra.

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A new approach for the homogenization of three-dimensional metallodielectric lattices : the periodic unfolding method

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In this presentation the classical multi-scale homogenization technique is associated to a new approach for the computation of the effective constitutive parameters of three-dimensional metallo-dielectric lattices. This approach is the periodic unfolding method [1, 2]. It is based on the decomposition of the fields in a main macroscopic part without micro-oscillations, and a corrector taking these micro-oscillations into account. To demonstrate the effectiveness of the proposed method, the effective permittivity for lattices of dielectric cubes and rods are compared to those obtained by the Maxwell-Garnett method. The corrector fields are also computed and studied as a function of frequency.

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Omnidirectional reflection for liquid surface waves propagating over a bottom with 1D periodic undulations

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It was known that there does not exist a complete band gap (along all directions) in infinite 1D photonic crystals, e.g., two dielectric layers stacking alternatingly. However, it was shown recently that a finite 1D photonic crystal can totally reflect incident light over a certain frequency range at all angles, i.e., omnidirectional total reflection [1-3]. The central idea resides in that if there are no propagating modes that can couple an incident wave of any angle, omnidirectional total reflection can occur.

In this work, we show theoretically the analog of omnidirectional total reflection in liquid surface waves propagating over a bottom with a 1D periodic undulation. We found that omnidirectional total reflection can exist in this system if the undulatory parameters are properly chosen. A general criterion that enables omnidirectional total reflection was proposed. The existence of omnidirectional total reflection for liquid surface waves propagating over a bottom with 1D periodic undulations may manifest potential applications.

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